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Feasibility of Using Light Water Reactors to Transmute Spent Nuclear Fuel

By Holly R. Trellue, and J. Wiley Davidson

Abstract

Over the past few decades, a variety of options have been proposed for transmuting spent nuclear fuel from Light Water Reactors (LWRs) in the United States. These options have included both reactor- and accelerator-based transmutation. Using LWRs to burn at least a portion of spent nuclear fuel offers advantages such as providing a reliable power source while burning the material and being able to use existing technology for the mission. Their use would also reduce the total amount of material that must be burned in an ADS, but the ADS would still be necessary to burn minor actinides that no longer have a high enough fission-to-capture ratio for irradiation in a reactor. Several LWRs are hoping to amend their licenses to be able to burn mixed oxide (MOX) fuel as part of the Materials Disposition (MD) program, and once this is complete, the process of amending additional reactor licenses to burn MOX for transmutation may become easier. This document discusses how this option would be feasible from a mass flow standpoint and portrays some of the experiences learned in the MD program.

1.0. Introduction

The use of existing Light Water Reactors (LWRs) to transmute a portion of spent nuclear fuel (SNF) is one of the approaches currently being studied for the Accelerator Transmutation of Waste (ATW) project. The idea of combining LWRs with accelerators as part of the nuclear fuel cycle (a multi-tier system) is based upon multi-tier nuclear fuel cycles in other countries (such as France and Japan) and the limited experience of the United States with mixed-oxide (MOX) fuels, which are a combination of uranium and plutonium (or higher actinide) oxides. Test MOX fuel rods were irradiated in U.S. nuclear reactors in the 1960s-1980s with commercial reactor-grade plutonium (Pu), and conclusions from these tests were that there were no health or safety impacts to the public from MOX fabrication or irradiation.[1] These tests set the foundation for the current Department of Energy (DOE) Materials Disposition (MD) program, which proposes to irradiate weapons-grade plutonium as MOX fuel in several existing LWRs. On the other hand, the most recent transmutation systems proposed in the U.S. send all transuranics and long-lived fission products to an accelerator-driven system (ADS) instead. There are many reasons for this, including the fact that in order to use plutonium from spent fuel in reactors, reprocessing (or some similar technology) would have to be employed, and this was banned in the 1970s. Second, using plutonium-containing fuels in reactors could pose safety concerns, so additional safety studies would have to be performed before these fuels could be licensed and burned in reactors. Third, there have been reservations about whether or not enough LWRs currently exist to burn all the necessary material within their existing lifetimes. Finally, the concern with transmuting SNF in a reactor is that along with plutonium, minor actinides and fission products are also present and must be transmuted. The addition of either of these materials decrease the reactivity and the fission-to-capture ratio in a system, and once a majority of the fissile material has been burned, it will be hard to maintain critical (k_{eff} of 1.0) in a reactor. Thus, complete transmutation of the material in a thermal reactor would probably not be possible, and an ADS (or comparable fast system) is still needed to transmute the remaining material. However, partial use of LWRs is a possibility, and this document addresses the other concerns with their use.

LWRs can provide a more reliable power source and they are a more proven technology than ADSs; thus, their use may expediate the transmutation process. LWRs are fairly efficient at burning plutonium; thus, it was recently proposed that LWRs be used to burn the plutonium and that the minor actinides would go straight to an ADS.[2,3] For proliferation reasons, however, it may be beneficial to keep the plutonium with the minor actinides and irradiate both in a LWR, but just plutonium burning is addressed in this document. The process of initiating MOX fuel use in LWRs for the MD program is discussed in Section 2, mass flows using data from the SNF storage/integrated database are given in Section 3, and a discussion on the use of nonfertile fuel (NFF) in LWRs is given in Section 4. All these pieces help answer the question of how existing LWRs could be used in transmuting SNF in the U.S.

2.0 Use of LWRs in the MD program

The capability of current commercial reactors to burn weapons-grade plutonium (i.e. that with a high fraction of Pu-239) was extensively examined as part of the DOE MD program. The decision by the Department of Energy to pursue reactor-based disposition of surplus weapons grade plutonium followed the 1994 recommendations of the National Academy of Sciences (NAS). The NAS concluded this approach would be effective for putting this material into a form that would be no more attractive for use in weapons applications that the plutonium contained in commercial reactor spent fuel – a form that meets the "Spent Fuel Standard". Although transmutation of SNF would involve the use of reactor-grade (not weapons-grade) Pu, the implementation process for burning the Pu in a reactor in the United States would be similar. However, it may be less extensive if it can build off what was learned and established in the MD program.

Review and selection of plutonium disposition alternatives took place under the provisions of the National Environmental Policy Act (NEPA) with ample opportunity for public participation. Approximately forty alternatives were initially evaluated. Selection of a dual track approach consisting of commercial reactor-based disposition of relatively pure forms of plutonium and immobilization and burial of relatively contaminated material was documented in a programmatic Environmental Impact Statement and Record of Decision released in January 1997, following nearly three years of public review and comment.

DOE's decision to employ a dual track approach for plutonium disposition was based on a desire to ensure a robust approach. It was recognized that reactor-based plutonium disposition would be based on well-developed technologies and thus would carry relatively small technical uncertainty. However, it was also recognized that political opposition to reactor-based disposition would be strong among certain segments of the public. DOE also recognized that those segments of the public would support immobilization and burial of surplus weapons grade plutonium. It was also recognized that technology development would be required to implement the immobilization alternative, and that technical uncertainty was not insignificant. The transmutation of SNF faces similar issues in that the use of LWRs would be technically beneficial to the mission, but public opposition and the need for almost complete transmutation dictate that their use would have to be in combination with ADSs. The use of an ADS in this program could be compared to the immobilization approach for the MD program in that it would probably be associated with less public opposition than reactor-based transmutation, but the use of LWRs as well makes the mission more technically efficient.

In 1997, following the release of the programmatic Record of Decision to use commercial reactors for plutonium disposition, DOE issued a request for expressions of interest in participating in the program (RFP). Interest was expressed by all of the commercial MOX fuel fabricators in Europe (BNFL, Cogema, Belgonucleaire, and Siemens) and by several utility owners of nuclear power plants. Commonwealth Edison was an early leader of utility efforts to encourage the DOE to pursue reactor-based plutonium disposition. DOE issued a request for proposals (RFP) for MOX fuel fabrication and irradiation services in early 1998. A similar request would have to be issued for burning reactor-grade Pu, although experience from the MD program may help reduce the time and effort required for gathering and analyzing responses because similar issues may be addressed (i.e. the introduction of Pu into the nuclear fuel cycle).

Initial efforts by industry to respond to the RFP were focused around each of four European MOX fuel fabricators. Each fabricator formed a consortium consisting of the fuel fabricator, an architect/engineering company, and one or more utility owners of nuclear power plants. Responses indicated that most LWRs (both PWRs and BWRs) could provide some capability, generally in the range of 30%–40% core loadings. The final contract was awarded in March 1999 to DCS, a consortium consisting of Duke Engineering Services, Cogema, Stone and Webster, and Duke Energy reactors (McGuire Units 1 and 2 and Catawba Units 1 and 2). No design modifications should be required to burn up to 40% MOX core loads in this program, and weapons-grade plutonium burn rates are estimated at 0.4 metric tons per year per reactor (6 MT of plutonium per reactor over the course of 15 years). Reactor-grade plutonium would follow this same path, most likely with as great as 40% MOX cores but would probably be associated with a smaller burn rate because reactor-grade Pu is not as fissile as weapons-grade Pu.

Early work to define technical issues associated with use of reactors for plutonium disposition was centered at the national laboratories. Oak Ridge focused its work on reactor performance issues and fuel qualification requirements, and Los Alamos worked on issues associated with fabrication of MOX fuel from Pu derived from weapons materials. Issues of particular concern were removal of gallium from the plutonium feed material (related to potential gallium-fuel cladding interactions), and requirements for Lead Test Assemblies (LTAs) for fuel qualification. Such fuel qualification issues are still not resolved. The process of separations and fabrication of reactor-grade plutonium is much more established (i.e. several European countries do it routinely), so less research and development would be required. Nonetheless, some fuel fabrication research and development (and/or use of LTAs) may still be necessary. In any case, a European collaborator will probably be necessary to complete the mission in a timely fashion.

DOE's experience with reactor-based plutonium disposition reveals several lessons that can be applied to new, complex nuclear energy undertakings under government sponsorship, such as the transmutation of waste. The time required to formulate and implement basic decisions is very long as a result of the requirements for public participation in decision making related to major federal actions. Issuance of the surplus plutonium disposition Record of Decision occurred almost seven years following the start of the program. Budget priorities can change with changes in administration, thereby affecting program schedules and fundamental program direction. These issues would also probably play a significant role in being able to use LWRs for transmutation; using only ADSs may or may not decrease the public/political challenges.

In addition, public opposition to things nuclear and DOE's record of not completing major programs have made commercial interests, particularly utility owners of nuclear power plants, very cautious about participating in such programs. Although many utilities expressed initial interest in participating in the MD program, very few were included in the final proposals, and one of the utilities from the winning consortium dropped out of the program soon after contract award. The remaining utility, Duke Energy, has indicated that its major reason for participating in the program is a desire to help the U.S. achieve its nonproliferation objectives. A similar incentive would have to be found for utilities to participate in a transmutation mission. Such an incentive could be the desire to reduce the waste existing in spent fuel pools and/or costs that may be burdened onto them for disposing of SNF in repositories.

Although the core loadings and burn rates for weapons-grade plutonium may not be the same for reactor-grade and recycled plutonium, there are some common elements with the MD mission. Operating license amendments are generally to technical specifications consistent with design features. Currently, licenses specify low-enriched uranium oxide fuels, while the proposed amendments specify MOX. License amendments for MOX that permit weapons-grade Pu MOX should cover reactor-grade Pu. Such license amendments could possibly also cover multi-recycle MOX, but potential safety impacts would need to be addressed. In particular, safety questions that would have to be answered include: are safety margins significantly reduced, does use of MOX increase possibility of new accidents, and are the effects and probability of accidents increased due to MOX fuel use? Basically the mechanical, thermal and physics performance of MOX fuel must be comparable to that of Low Enriched Uranium (LEU) fuel. Design Basis Accident scenarios should prove that 1) fuel damage should not occur during operation and if it occurs, such damage should not prevent a control rod insertion, 2) a coolable core geometry must be maintained, and 3) radioactivity releases during an accident should not be underestimated.[1] Research and Development efforts are already underway to address these issues for the MD program, and it is assumed that issues surrounding reactor-grade plutonium from SNF should be less of a concern because the plutonium is less fissile. The addition of minor actinides in the MOX fuel may complicate licensing issues further, but licensing and/or irradiation should still be feasible if that alternative is pursued.

3.0 Mass flows and use of commercial LWRs for transmutation

There are currently more than 100 nuclear reactors operating in the United States. Between May 2000 and April 2001, two stations (five reactors) received license renewals (of 20 years) and more plan to apply (electricity blackouts in

California in 2001 and other events have recently provided an incentive for more nuclear power) in the near future. Although Pu-containing fuel has not yet specifically been licensed for any U.S. reactors, four Duke Power PWRs (Westinghouse 17x17) plan to undergo MOX licensing for the MD mission as discussed in Section 2, and CE System 80 reactors were actually designed to burn full cores of MOX fuel. Such design includes containment penetrations for additional control rod systems, and design basis analyses have been performed for the use of MOX.

Calculations show that 48000 metric tons of heavy metal (MTHM) will be loaded in existing LWRs past the year 2011 (see Table 1).[a] Using the following assumptions, it can be calculated that the ~740 metric tons (MT) of legacy plutonium (87 GT of spent nuclear with ~1% transuranic (TRU) content and 0.85w% Pu in the TRU) can be transmuted to about 67% (740 MT + 740*0.7 (the remainder after the first burn/recycle) + 740*0.7*0.7 (what remains after the second burn/recycle), which equals about 1600 MT of material loaded into reactors and 254 MT remaining after reactor-based transmutation ($740*0.7^3$)). At this point, the fission-to-capture ratio of the material is probably too low to continue burning in a reactor anyway, so it should be sent to an ADS at this point. The calculation process used was verified in Appendix A.

Assumptions:

- All reactors will operate to their current lifetimes but only those operating past 2015 were considered for this mission (assuming 2011 is the first year of availability, then they could burn MOX for at least 5 years);
- All reactors can be licensed for MOX fuel burning by 2011 (if the licensing process takes longer, then it is assumed this bullet will balance the previous one in that the lifetimes of applicable reactors will be extended);
- Each fuel rod is burned in the reactor for four years (3 16-month cycles);
- Each reactor (on average) can be loaded with a one-third core of MOX fuel;
- The heavy metal in the MOX fuel can be loaded with 10w% reactor-grade Pu;
- Each MOX fuel rod can achieve a burnup of 30w% over its four years in a LWR;
- Up to two recycles of the plutonium can be used.

[a] www.eia.doe.gov/fuelnuclear.html

Table 1. Existing LWRs, Emphasizing Those Presumed to be Available for MOX Burning

Utility	Reactor	Year of shut-down	yrs. A-vail-a-ble	kg HM loading per assembly	# assem-blies	MTHM loaded / year (if each rod is burned 4 years)	Type of Reactor
Alabama Power Company	Farley 1	2017	6	450	716	483.3	WE 17x17 3LP
	Farley 2	2021	10	450	558	627.75	WE 17x17 3LP
Arizona Public Service Company	Palo Verde 1	2024	13	410	368	490.36	CE System 80 CE80
	Palo Verde 2	2025	14	410	384	551.04	CE System 80 CE80
	Palo Verde 3	2027	16	410	380	623.2	CE System 80 CE80
Arkansas Power and Light Company	Arkansas Nuclear 1	2014	3				
	Arkansas Nuclear 2	2018	7	415	636	461.895	CE 16x16 CE
Baltimore Gas and Electric Company	Calvert Cliffs 1*	2034	23	380	888	1940.28	CE 14x14 CE
	Calvert Cliffs 2*	2036	25	380	700	1662.5	CE 14x14 CE
Boston Edison Company	Pilgrim 1	2012	1				
Carolina Power and Light Company	Brunswick 1	2016	5	185	560	129.5	GE BWR/4-6 4
	Brunswick 2	2014	3				
	Harris 1	2026	15	450	276	465.75	WE 17x17 3LP
	Robinson 2	2010	-1				
Cleveland Electric Illuminating Company	Perry 1	2026	15	185	972	674.325	GE BWR/4-6 6
Commonwealth Edison Company	Braidwood 1	2028	17	450	324	619.65	WE 17x17 4LP
	Braidwood 2	2028	17	450	344	657.9	WE 17x17 4LP
	Byron 1	2025	14	450	520	819	WE 17x17 4LP
	Byron 2	2027	16	450	344	619.2	WE 17x17 4LP
	Dresden 1	1984	-27				
	Dresden 2	2010	-1				
	Dresden 3	2013	2				
	LaSalle County 1	2024	13	185	1228	738.335	GE BWR/4-6 5
	LaSalle County 2	2024	13	185	1132	680.615	GE BWR/4-6 5
	Quad Cities 1	2013	2				
	Quad Cities 2	2013	2				

	Zion 1	2013	2				
	Zion 2	2014	3				
Consolidated Edison Company of NY	Indian Point 1	1980	-31				
	Indian Point 2	2013	2				
Consumers Power Company	Big Rock Point	2000	-11				
	Palisades	2011	0				
Dairyland Power Cooperative	LaCrosse	1987	-24				
Detriot Edison Company	Enrico Fermi 2	2025	14	185	900	582.75	GE BWR/4-6 4
Duke Power Company	Catawba 1	2025	14	450	484	762.3	WE 17x17 4LP
	Catawba 2	2026	15	450	444	749.25	WE 17x17 4LP
	McGuire 1	2021	10	450	616	693	WE 17x17 4LP
	McGuire 2	2023	12	450	628	847.8	WE 17x17 4LP
	Oconee 1 *	2033	22	464	886	2261.07	BW 15x15 LLP
	Oconee 2 *	2033	22	464	856	2184.51	BW 15x15 LLP
	Oconee 3 *	2034	23	464	808	2155.74	BW 15x15 LLP
Duquesne Light Company	Beaver Valley 1	2016	5	450	576	324	WE 17x17 3LP
	Beaver Valley 2	2027	16	450	260	468	WE 17x17 3LP
Florida Power Corporation	Crystal River 3	2016	5	464	608	352.64	BW 15x15 LLP
Florida Power and Light Company	St. Lucie 1	2016	5	380	964	457.9	CE 14x14 CE
	St. Lucie 2	2023	12	380	544	620.16	St. Lucie 2 CE
	Turkey Point 3	2012	1				
	Turkey Point 4	2013	2				
Georgia Power Company	Hatch 1	2014	3				
	Hatch 2	2018	7	185	1815	587.6	GE BWR/4-6 4
	Vogtle 1	2027	16	450	408	734.4	WE 17x17 4LP
	Vogtle 2	2029	18	450	238	481.95	WE 17x17 4LP
GPU Nuclear Corporation	Three Mile Island 1	2014	3				
	Oyster Creek	2009	-2				
Gulf States Utilities Company	River Bend 1	2025	14	185	956	619.01	GE BWR/4-6 4
Houston Lighting and Power Company	South Texas 1	2027	16	540	236	509.76	South Texas 4LP
	South Texas 2	2028	17	540	188	431.46	South Texas 4LP
IES Utilities, Inc.	Duane Arnold	2014	3				
Illinois Power Company	Clinton 1	2026	15	185	724	502.275	GE BWR/4-6 6
Indiana Michigan Power Company	Cook 1	2014	3				
	Cook 2	2017	6	450	733	494.775	WE 17x17 4LP
Kansas Gas and Electric Company	Wolf Creek 1	2025	14	450	488	768.6	WE 17x17 4LP
Long Island Power	Shoreham	1987	-24				

Authority							
Louisiana Power and Light Company	Waterford 3	2024	13	415	520	701.35	CE 16x16 CE
Maine Yankee Atomic Power Company	Maine Yankee	2008	-3				
Nebraska Public Power District	Cooper Station	2014	3				
New York Power Authority	FitzPatrick	2014	3				
	Indian Point 3	2015	4				
Niagara Mohawk Power Corporation	Nine Mile Point 1	2008	-3				
	Nine Mile Point 2	2026	15	185	640	444	GE BWR/4-6 5
North Atlantic Energy Service Corporation	Seabrook	2030	19	450	208	444.6	WE 17x17 4LP
Northeast Utilities Service Company	Millstone 1	2010	-1				
	Millstone 2	2015	4				
	Millstone 3	2025	14	450	332	522.9	WE 17x17 4LP
	Haddam Neck	2007	-4				
Northern States Power Company	Monticello	2010	-1				
	Prairie Island 1	2013	2				
	Prairie Island 2	2014	3				
Omaha Public Power District	Fort Calhoun	2013	2				
Pacific Gas and Electric Company	Diablo Canyon 1	2021	10	450	464	522	WE 17x17 4LP
	Diablo Canyon 2	2025	14	450	484	762.3	WE 17x17 4LP
	Humboldt Bay	1976	-35				
PECO Energy Company	Limerick 1	2024	13	185	1838	1105.1	GE BWR/4-6 4
	Limerick 2	2029	18	185	654	544.455	GE BWR/4-6 4
	Peach Bottom 2	2013	2				
	Peach Bottom 3	2008	-3				
Pennsylvania Power and Light Company	Susquehanna 1	2022	11	185	1628	828.245	GE BWR/4-6 4
	Susquehanna 2	2024	13	185	1484	892.255	GE BWR/4-6 4
Portland General Electric Company	Trojan	1992	-19				
Public Service Electric and Gas Company	Hope Creek	2026	15	185	1240	860.25	GE BWR/4-6 4
	Salem 1	2016	5	450	708	398.25	WE 17x17 4LP
	Salem 2	2020	9	450	556	562.95	WE 17x17 4LP
Rochester Gas and Electric Corporation	Ginna	2009	-2				
Sacramento Municipal Utility District	Rancho Seco	1989	-22				

South Carolina Electric and Gas Company	Summer	2035	24	450	504	1360.8	WE 17x17 3LP
Southern California Edison Company	San Onofre 1	1992	-19				
	San Onofre 2	2013	2				
	San Onofre 3	2013	2				
System Energy Resources, Inc.	Grand Gulf 1	2022	11	185	1660	844.525	GE BWR/4-6 6
Tennessee Valley Authority	Browns Ferry 1	2013	2				
	Browns Ferry 2	2014	3				
	Browns Ferry 3	2016	5	185	1030	238.19	GE BWR/4-6 4
	Sequoyah 1	2020	9	450	429	434.36	WE 17x17 4LP
	Sequoyah 2	2021	10	450	472	531	WE 17x17 4LP
	Watts Bar 1	2035	24	450	450	1215	WE 17x17 4LP
Toledo Edison Company	Davis-Besse	2037	26	464	520	1568.32	BW 15x15 LLP
TU Electric	Comanche Peak 1	2030	19	450	205	438.19	WE 17x17 4LP
	Comanche Peak 2	2033	22	450	88	217.8	WE 17x17 4LP
Union Electric Company	Callaway	2024	13	450	548	801.45	WE 17x17 4LP
Vermont Yankee Nuclear Power Corporation	Vermont Yankee	2012	1				
Virginia Power	North Anna 1	2018	7	450	622	489.825	WE 17x17 3LP
	North Anna 2	2020	9	450	567	574.09	WE 17x17 3LP
	Surry 1	2012	1				
	Surry 2	2013	2				
Washington Public Power Supply System	Washington Nuclear 2	2023	12	185	1196	663.78	GE BWR/4-6 5
Wisconsin Electric Power Company	Point Beach 1	2010	-1				
	Point Beach 2	2013	2				
Wisconsin Public Service Corporation	Kewaunee	2014	3				
Yankee Atomic Electric Company	Yankee Rowe	1992	-19				
						total MTU =	47799.54175
	* Renewed License					total HM =	4779.954175
				Amount of TRU that can be loaded assuming full cores of MOX fuel and 10w% Pu or TRU in heavy metal of MOX			

Despite this optimistic, “best case” scenario using all reactors, it is probably more accurate to assume that not all LWRs could be licensed for MOX fuel. As a result of the MD program, one common reactor currently undergoing licensing for MOX fuel is a Westinghouse (WE) 17x17 Power Water Reactor (PWR).

Assuming the licensing process is completed, licensing for other WE PWRs should be more straightforward. Thus, assuming all WE 17x17 PWRs and the CE System 80s that have been designed for a full core of MOX actually burn a full core of MOX fuel, then calculations show that ~2150 MT of TRU could be burned in these reactors (~720 MT with one-third cores of MOX) up to ~30% burnup within existing lifetimes. By extending the lifetimes of all reactors by 20 years, just these reactors alone can burn 5600 MT TRU with full cores and ~1870 MT TRU with one-third cores.

An alternative way of performing this calculation is to examine the commercial sector capability for transmuting a portion of SNF as MOX in LWRs. For this scenario, the reactor power requirement, assuming the use of Advanced LWRs, 100% MOX core loadings, and 50 GWd/MTHM burnup, is about 46 GWt. For a 30% core loading, this is equivalent to a required capacity of 153 GWt. This is about half of the 300 GWt installed capacity of existing LWRs. Thus, the transmutation of at least the plutonium could be supported if roughly 50% of the current LWR reactors could achieve 30% licensable MOX core loadings (as shown by the mass calculations above). This still assumes a burnup of approximately 30%, but burnups up to 70% may be achievable. Such deeper burn scenarios could be accommodated using more of the existing installed capacity or higher core loadings. In either approach, design modifications may drive the ability to relicense. Alternatively, multiple recycle passes and/or a more efficient fuel type (such as non-fertile fuel (NFF) as will be discuss in the next section) could increase the total achievable burnup.

4.0 Use of Non-fertile Fuel in LWRs

Although the use of MOX fuel in LWRs is advantageous due to the large experience base associated with it, the presence of uranium offsets the efficiency of burning just the plutonium (fissions will occur in the uranium as well as the plutonium (decreasing the percentage of plutonium transmuted), and neutron capture in the uranium leads to the production of additional plutonium). Therefore, plutonium would be burned more efficiently in a uranium-free matrix so that a majority of the neutron interactions destroy the plutonium, not produce it. One solution for this is to use a nonfertile (uranium-free) fuel that consists of plutonium (and/or other minor actinides) stabilized in an inert matrix.[4,5,6] Burnable poison (most commonly erbium) is used to control reactivity and power peaking. The most common inert (neutronically) materials typically considered are ZrO_2, CeO_2, MgO, Al_2O_3, and even ThO_2 (which is fertile and leads to the breeding of uranium, which is undesirable in this application). In the past, one-third MOX-fueled cores with <10% plutonium have been licensed within safety boundaries, and similar core load fractions would be expected for NFFs. Studies with NFF have ranged from a one-eighth core to a full-core loading, and preliminary safety issues (including reactivity coefficients) are not a concern in either case if a sufficient amount of burnable poison is used. It is also even possible to make the fuel more robust by including a small fraction of uranium (but much smaller than that found in MOX fuel).[7] Minor actinides should also be able to be included in the NFF along with plutonium and although this will decrease the burnup, it would be beneficial from a proliferation standpoint. The fact that partial MOX-fueled cores are already licensed may make them faster to implement than a new fuel type, but the burnup rate of plutonium and MAs in MOX fuel is only 30% to 40% compared to the 70% to 80% obtainable with uranium-free cores in a single pass.[8,3]

5.0 Conclusions

The use of Light Water Reactors to burn at least the plutonium from SNF is beneficial from several standpoints. Primarily, it provides a reliable power source and electricity generation while removing some of the concerns associated with putting SNF in a repository. The use of ADSs is probably still needed for complete burns, but burning some material in reactors would reduce the number of systems necessary. Along with LWRs, other types of reactors have been examined for this mission (i.e. gas-cooled thermal reactors or even fast reactors), but since those types have been either licensed or built in the United States, a new reactor type may take even longer to implement than relicensing existing LWRs to burn plutonium. Since there is a huge experience base with MOX fuel in Europe and some reactors in the U.S. are already undergoing licensing for MOX fuel, transmuting SNF in MOX fuel will probably be the quickest way to implement the program (probably even more so than using ADSs). The MD program already proposes to burn MOX fuel in commercial LWRs, and this could potentially make it easier to use MOX and LWRs to transmute Pu (and/or minor actinides) from SNF than the traditional ADS. In terms of mass flow and power production, it is indeed feasible to burn the legacy Pu up to 67% using a existing LWRs within their current lifetimes and one-third core loadings of MOX fuel. However, to obtain more complete burns, additional LWRs, a larger core fraction of MOX fuel, and/or the use of uranium-free fuels may become necessary. Nonetheless, the possibility of using LWRs in waste transmutation should definitely be further explored.

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Appendix A. Verification of Mass Flow Assumptions

The calculations performed in Section 3 can be verified based on the prediction of burning 0.4 MT/year of weapons-grade Pu in the MD program. Take the four reactors being proposed for that mission (WE 17x17s, Catawba 1 and 2 and McGuire 1 and 2). They have 217.8, 199.8, 277.2, and 282.6 metric tons heavy metal respectively loaded in all assemblies at any time (see Table 1). Assuming 16-month cycles and 3 cycles per fuel rod (i.e. each assembly is reloaded every 4 years), then the number of metric tons loaded on average per year per reactor is 61.09 MTHM. Assuming the weapons-grade plutonium in MOX fuel comprises 5% of all heavy metal and 40% of the core, then 1.22 MT plutonium can be loaded per year per reactor. Then assuming that it takes four years to burn 30% of the material in each region and three different regions, it leads to a burn rate of 0.275 MT plutonium per year. The 30% burnup is assumed for reactor-grade plutonium from spent fuel, so it makes sense that weapons-grade plutonium can burn more than 30% over four years, which is probably why the estimated burn rate for the MD program is 0.4 MT/yr, not 0.275 MT/yr.